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Utilising an advanced technology of people tracking in vibration serviceability application

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ABSTRACT

There is a continuous development in the facilities used for experimental measurements of human-induced vibrations due to walking of people in real-life structures. These facilities can be classified into three categories:

1. systems used to measure walking forces,
2. systems used to measure structural dynamic properties and vibration responses and
3. equipment required to locate the position of people within the structure.

In recent years, state-of-the-art technologies have enabled both direct and indirect measurement of walking forces and vibration responses with improved accuracy. However, determining people's position on the structure they occupy and dynamically excite is still a challenge, despite its importance. This is due to the limitations and lack of accuracy of existing systems used for this purpose.

This paper presents an advanced system based on the Ultra-WideBand (UWB) technology to track the position of multiple people within civil engineering structures. It is demonstrated that this system has the capability of providing measurements of people's positions in real-time, with around 50 cm accuracy, using wearable compact tags. In addition to the accuracy, the simple setting up and capability to track people's positions in different types of structures are advantages over other types of body location tracking systems. Incorporating the above mentioned systems to measure simultaneously walking-induced forces, realistic time-varying locations of these forces and the corresponding time-varying vibration responses has created an unprecedented opportunity to boost considerably research pertinent to human-induced vibration. This will be based on invaluable but, until now, difficult to conduct real-life simultaneous measurements of these three key time-varying walking-force parameters.

Keywords: Position tracking, walking path, vibration serviceability, floors, human-induced vibrations.

INTRODUCTION

Vibration serviceability criteria due to human activities is increasingly becoming a critical factor in designing civil structures including building floors and footbridges [1–3]. This criterion is based on three key elements [4]:

- vibration source i.e. human-induced forces due to human activities, such as walking and jumping,
- vibration transmission path i.e. dynamic properties of the structure and
- vibration receiver i.e. sensitive equipment or perception of human occupants of the vibration responses.

While the dynamic properties can be identified using the currently available measurement facilities, recently, it became possible to measure human-induced forces and corresponding vibration responses simultaneously, with an acceptable accuracy [5,6]. However, measuring the positions and walking routes of people, as dynamic exciters and vibration receivers, is still a challenge due to the technical limitations and lack of accuracy for relevant available measurement facilities [7].

This paper proposes utilising an advanced system of people tracking based on the Ultra-WideBand (UWB) technology to provide direct measurements of multiple-pedestrian walking locations on building floors. The unique UWB system can be easily set up, and measure people's locations with sub-meter accuracy. The system was tested by performing walking tests on a full-scale laboratory floor, while direct measurements of people's locations, their walking forces and the corresponding vibration responses were measured simultaneously.

APPLICATION OF UWB TECHNOLOGY

UWB technology has a wide range of applications, including positioning, security and communications [8,9]. For positioning, recent developments have made it possible to provide localisation in construction sites, hospitals and factories. The large bandwidth of the UWB signal and its ability to mitigate the loss of energy in multipath environments are the main advantages of this technology [9].

In this paper, a system based on this technology is utilised in the context of vibration serviceability. It has been tested to track people's locations while walking forces and the corresponding vibration responses are measured simultaneously. The system comprises a wearable signal emitters (tags) which send pulses to signal receivers (anchors). A central server utilises the information of time and angle of arrival to estimate the positions using a triangularisation technique as shown in Fig. 1.

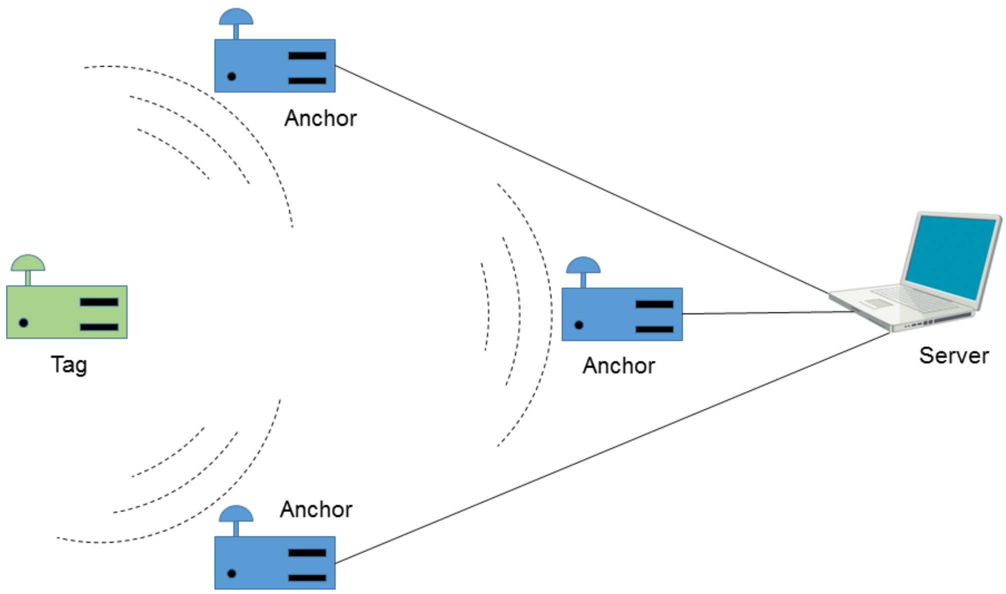


Figure 1. Overview of UWB tracking system components.

EXPERIMENTAL TEST

The experimental work carried out in this paper utilises state-of-the-art facilities to extract the dynamic properties of a test structure and provide direct measurements of people's locations, their walking forces and the corresponding vibration responses.

Test structure

The test structure is a full-scale laboratory floor located in the Structures Lab at the University of Exeter (Fig. 2). The floor is 7.5 m long and 5.0 m wide and it consists of Sandwich Plate System (SPS) plates supported by steel beams.

Multiple-input multiple-output (MIMO) modal testing was performed to identify the dynamic properties of the structure. Two APS400 [10] shakers were utilised to apply uncorrelated random excitation force to the floor and the forces were measured indirectly using Endevco 7754-1000 piezoelectric accelerometers [11] to measure the acceleration of the shakers' moving mass. Floor vibration responses were measured using 19 Honeywell QA750 accelerometers [12] on a 7.5*5.0 m grid as shown in Fig. 2. The frequency response functions (FRFs) were measured using a Data Physics DP730 24-bit spectrum analyser. The modal properties were identified using multiple degree of freedom (MDOF) curve fitting tool available in the ME'Scope software [13]. A summary of the identified modes up to 20 Hz are shown in Fig. 3.

Walking tests

Two test subjects (TSs) participated in the walking tests. To track their locations, each TS was instrumented with a compact wearable tag on his left hand wrist. Four anchors were deployed for the test and positioned just outside the four corners of the floor. The relative positions of the anchors were measured and used as input in the central server of the tracking system to calculate the positions of the tags.

The walking forces were measured indirectly [5] using two synchronised wireless APDM Opal^{TM} [14] monitors (Fig. 4). The Opal^{TM} monitors were attached to the seventh cervical vertebra (C7) at the lower neck of the TSs.

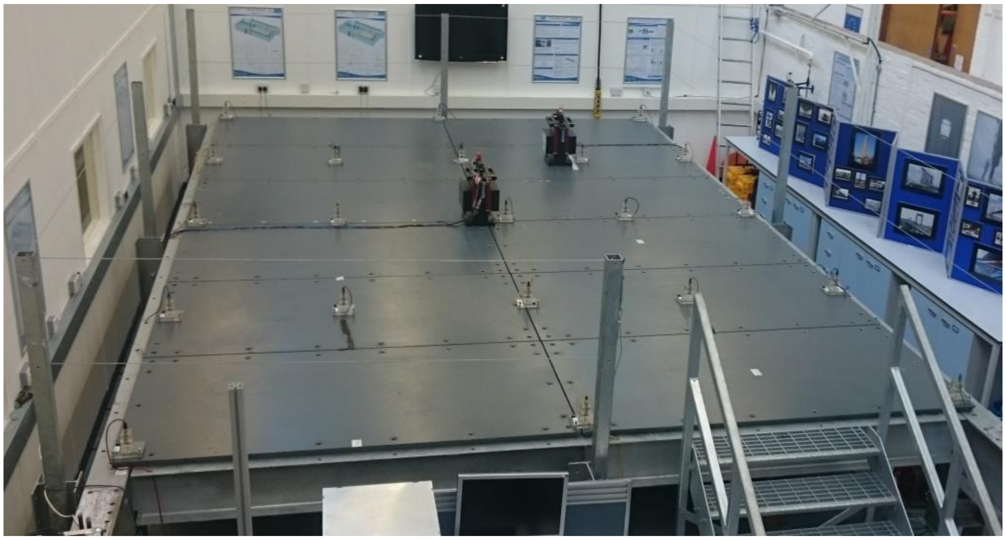


Figure 2. Full-scale laboratory test structure.

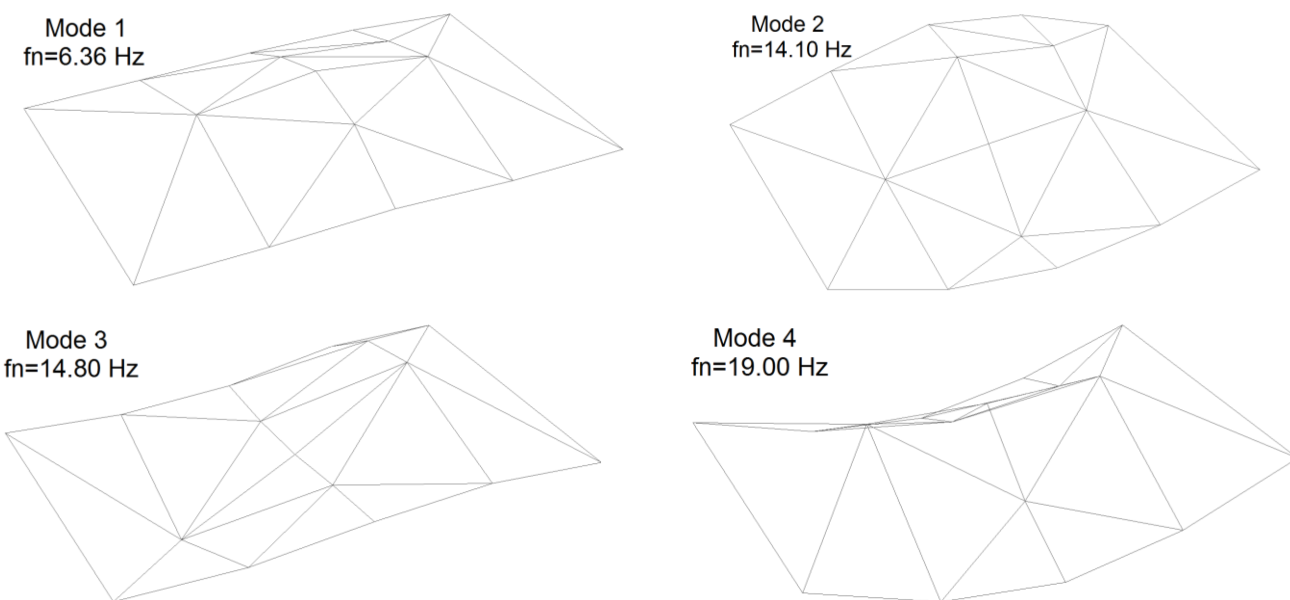


Figure 3. Experimentally identified mode shapes of the 1st, 2nd, 3rd and 4th vertical bending modes.

Figure 4. APDM Opal^{TM} monitor [14].

To measure the floor vibration responses, three accelerometers were positioned at the anti-nodes of the 1st, 2nd and 3rd vibration modes. The accelerometers were synchronised with the Opal™ monitors by shaking them manually after attaching them to each other so that their signals can be synchronised. A video camera was fixed at the top of the structure to compare the tracked with the real positions of the TSs. The data acquisition starting times of the people tracking system, the Opal™ monitors and the video camera were recorded to synchronise their data.

Two walking routes were selected for this test:

- diagonal route, where the TSs walk across the diagonal of the structure at the same time (Fig. 5a), and
- 8-shape walking route as shown in Fig. 5b.

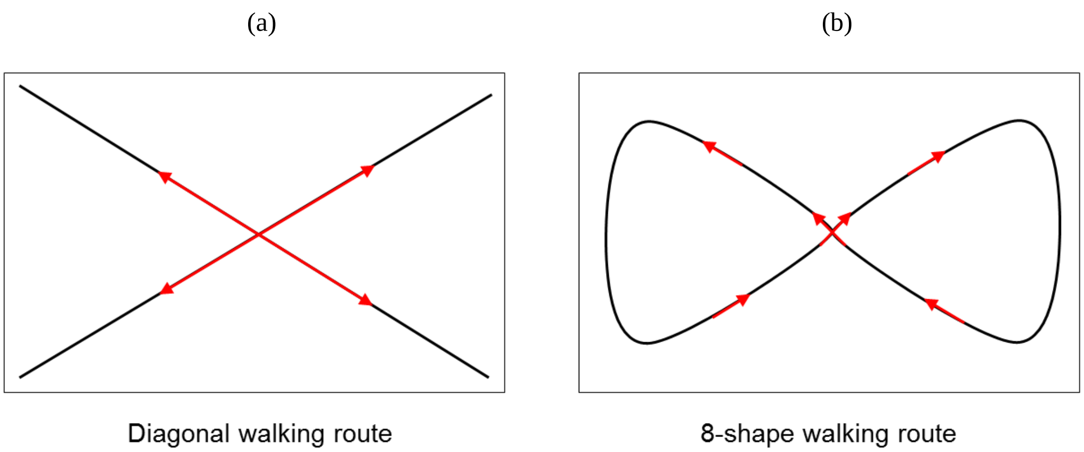


Figure 5. (a) Diagonal and (b) 8-shape walking routes.

The former walking route was chosen to compare the locations of the TSs with their corresponding vibration responses. The second walking route was used to test the performance of the tracking system for a more complex walking route.

RESULTS AND DISCUSSION

The tracked and real positions of the TSs, their walking forces and the corresponding vibration response for one walking test in the diagonal route are presented in Fig. 6. The green and blue dots in Fig. 6a refer to the tracked positions of TS1 and TS2, respectively. The corresponding real locations of the TSs were extracted as images from the recorded video and merged for visualization purposes as shown in Fig. 6a. It is obvious that despite the tracked positions are not always accurate, they are consistent with the real locations, with good agreement between them most of the time.

Considering the mode shape of the first vibration mode (Fig. 3), the tracked positions of the TSs (Fig. 6a) are related to the measured vibration response (Fig. 6d). The maximum vibration response is obtained when the TSs were approximately walking in the middle of the floor, while lower vibration responses were recorded as TSs approach the corners (Fig.6a and Fig.6d).

Fig. 7 shows the heat map, corresponding to the tracked positions in Fig. 6a, and its envelope for the two TSs, individually and collectively. The heat map is generated after the tracked positions were interpolated to obtain denser points. This plot can be used as an indication of the tracked positions and the corresponding proportion of time spent by TSs on the floor.

The heat map of tracked positions for the two TSs in the 8-shape walking route is presented in Fig. 8. It can be seen that there are relatively more tracked locations in the middle of the structure, which is consistent with the planned walking route (Fig. 5b). The differences between the planned walking route (Fig. 5b) and the tracked positions (Fig. 8) could be explained by the inevitable errors of the tracking system and the natural inability of TSs to walk perfectly on the planned walking route with a constant speed.

(a)

(b)

(c)

(d)

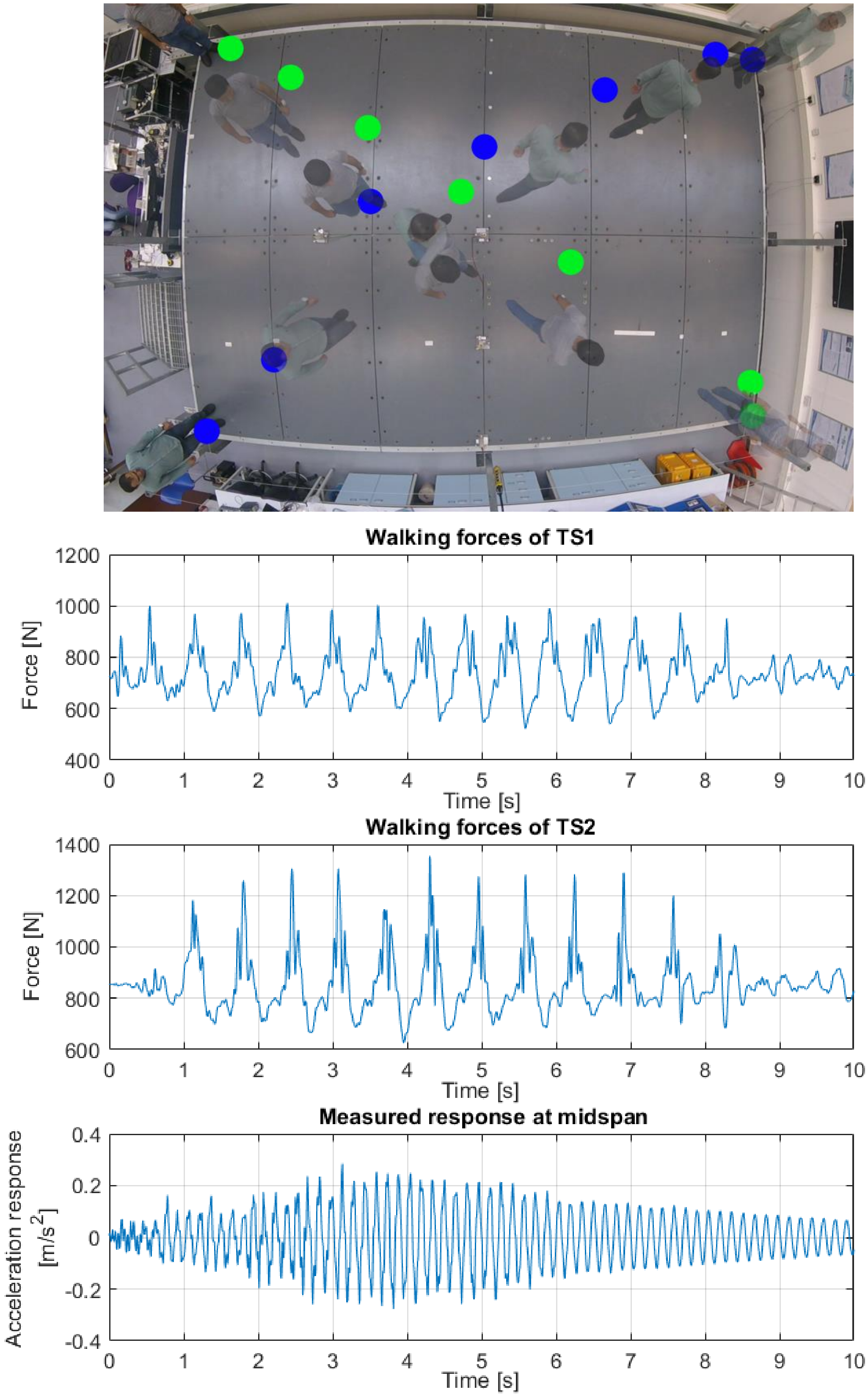
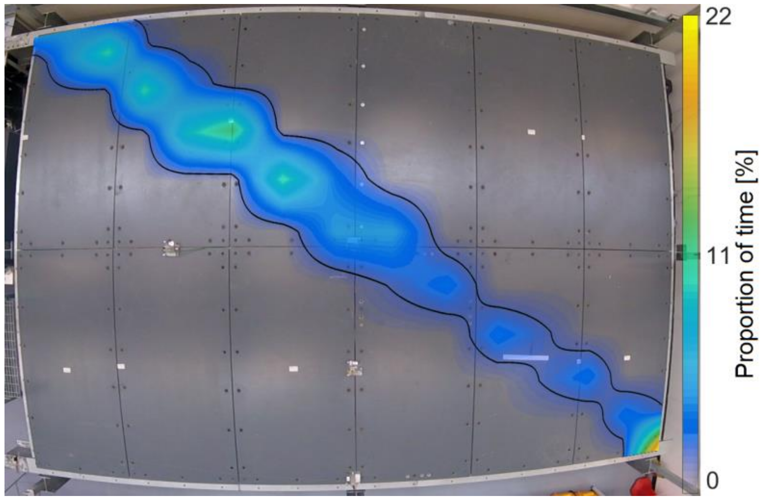
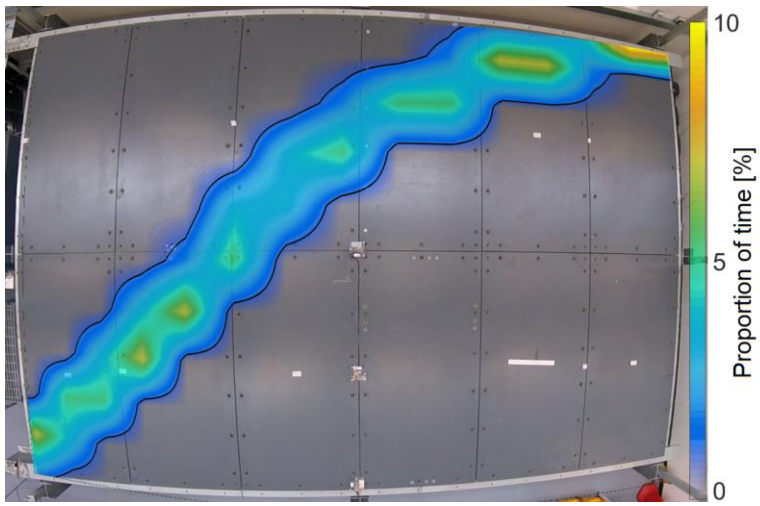


Figure 6. (a) Tracked (green and blue dots) and real locations of TSs, (b) measured walking forces of TS1, (c) measured walking forces of TS2 and (d) the corresponding vibration response measured in the middle of the structure.

(a)



(b)



(c)

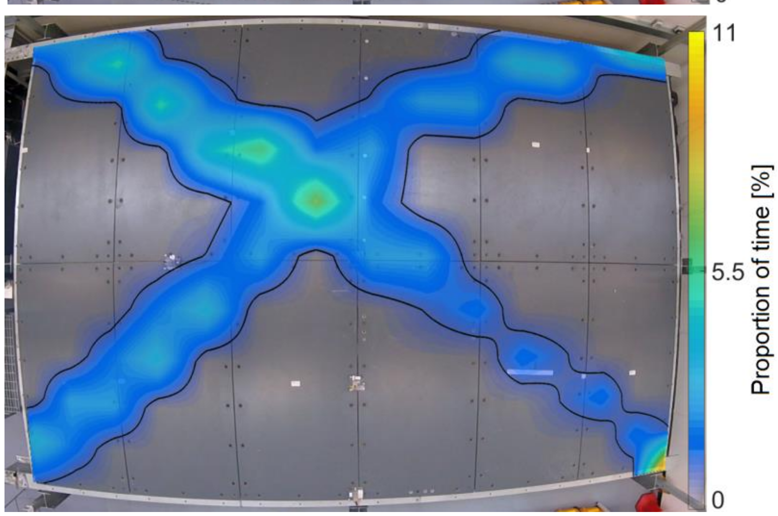


Figure 7. The heat map of the tracked positions for (a) TS1 (b) TS2 and (c) both test subjects in a walking test in the diagonal walking route.

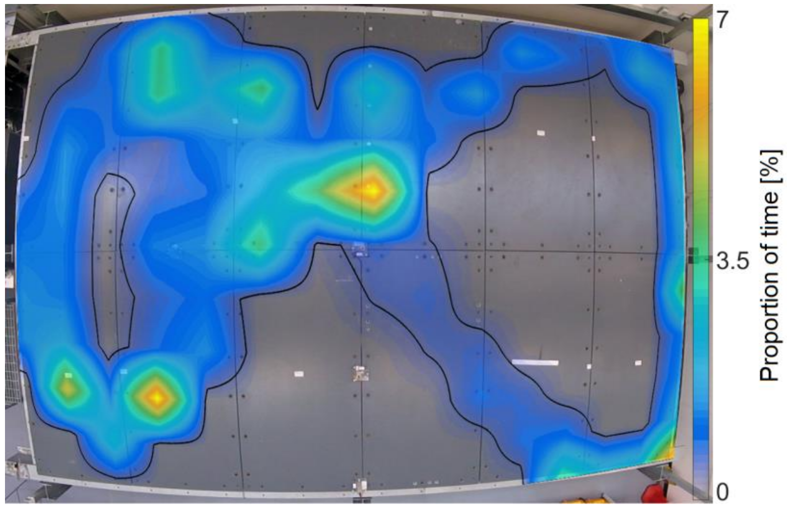


Figure 8. The heat map of the tracked positions for the two TSs in a walking test in the 8-shape walking route.

CONCLUSIONS

This paper proposes utilising a unique system based on the advanced technology of UWB to collect data regarding people's positions and movements in indoor building floors for vibration serviceability applications. To the best knowledge of the authors, this is the first attempt to monitor the people's locations in this context. The accuracy obtained by using this system and its easy implementation are promising for extensive use in future research. It has been shown that it finally became possible to measure directly the position of people, their walking forces and the corresponding vibration responses simultaneously, using state-of-the-art technology systems with an acceptable accuracy.

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